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The impact of project-based learning on enhancing students' mathematical communication skills

Mustika Helma*, [a], Sri Yunita Ningsih[b], Wahyuni[c]
[a-c]STKIP Insan Madani, Airmolek, Riau, Indonesia, 29352

Abstract.
This study investigates the impact of the Project-Based Learning (PBL) model on the mathematical communication skills of eighth-grade students at SMP Negeri 3 Sungai Lala. The research was motivated by the need to improve students' ability to articulate mathematical ideas clearly and accurately, a skill often found lacking in conventional classroom settings. Adopting a quasi-experimental design with a posttest-only control group, two classes were selected: one as the experimental group receiving PBL instruction, and the other as the control group receiving conventional teaching methods. The PBL approach was implemented by engaging students in structured projects that required collaborative problem-solving, critical thinking, and the presentation of mathematical concepts in both oral and written forms. Data were collected through a standardized mathematical communication skills test designed to assess clarity of explanation, accuracy of reasoning, and the effective use of mathematical representations. Statistical analysis using the Independent Samples t-test revealed a significant difference in performance between the two groups ($p < 0.05$). Students exposed to the PBL model achieved notably higher scores, indicating superior proficiency in expressing and justifying mathematical ideas compared to their peers in the conventional group. These findings highlight the potential of PBL as an alternative instructional strategy to enhance mathematical communication skills, aligning with current educational goals that emphasize active learning and the development of 21st-century competencies. The study recommends broader application of PBL in mathematics education, particularly in contexts where fostering communication and reasoning is a priority.

Keywords:
Project-Based Learning; mathematical communication; secondary school students

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INTRODUCTION

Education is a fundamental process in developing human potential and shaping individual character. Etymologically, the term "education" originates from the Latin word "educare," which signifies "to lead out" or "to develop" (Danim, 2017). This etymology underscores the primary objective of education, which is to propel students beyond their inherent limitations and unlock their full potential. From a contemporary perspective, Law Number 20 of 2003 pertaining to the National Education System defines education as a deliberate and structured endeavor to establish a conducive learning environment and facilitate a learning process that enables students to actively develop their multifaceted potential, encompassing spiritual, intellectual, emotional, and practical aspects. Learning, as the cornerstone of the educational process, as elucidated by Sudjana (2020), constitutes a relatively enduring transformation in behavior resulting from accumulated

* Corresponding author.
E-mail address: helmamustika@gmail.com

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experience.

In the 21st century, the educational paradigm has undergone a profound transformation. The learning process has shifted from a one-directional knowledge transfer to a multifaceted approach that emphasizes the development of critical thinking, creativity, collaboration, and communication skills. The Organisation for Economic Co-operation and Development (OECD, 2018) underscores the significance of learning that addresses global challenges and local needs. Numeracy literacy, considered a fundamental competency for every individual, is highlighted as a crucial component of relevant learning. In this context, mathematics assumes a strategic role, not only as a discipline that imparts numeracy skills, but also as a means of fostering logical, systematic, and critical thinking patterns that can be applied across diverse life domains.

Mathematics is not merely a collection of formulas or mechanical procedures. According to Isrok'atun and Rosmala (2021), mathematics is a cognitive framework that can be applied to diverse life situations. The efficacy of mathematical learning is assessed not only by students' problem-solving abilities, but also by their capacity to articulate mathematical concepts clearly and precisely. The National Council of Teachers of Mathematics (NCTM, 2000) recognized mathematical communication skills (MCS) as one of the fundamental standards in mathematical education. These skills encompass the ability to convey mathematical ideas, concepts, and reasoning both orally, in writing, and visually, as well as to comprehend and evaluate the mathematical perspectives of others (Tinungki et al., 2022; Tong et al., 2021; Kamid et al., 2020). Gravemeijer et al. (2017) underscored that MCS is an integral component of numeracy literacy, which is crucial for academic achievement and decision-making in everyday life.

Regrettably, numerous studies indicate that students' MCS in Indonesia remains at a concerning level. The 2019 Trends in International Mathematics and Science Study (TIMSS) reported that 73% of Indonesian students aged 13–14 years had an MCS below the intermediate level, highlighting a substantial competency gap. This phenomenon was also observed at SMP Negeri 3 Sungai Lala, based on preliminary observations. Daily test data revealed that 82% of eighth-grade students failed to attain the ideal score of 70. Specifically, class VIII-A, comprising 31 students, obtained an average of 41.93, while class VIII-B, with 29 students, achieved an average of 47.93. Consequently, the overall average of the two classes was 44.93, and the standard deviation was 8.21. These figures underscore a significant disparity between learning objectives and actual student performance.

An analysis of the learning conditions at the school identified several factors contributing to the low MCS. Firstly, the predominant learning method is a lecture-based approach with minimal interaction, where the teacher primarily serves as an information source while students assume a passive role (Hattie, 2012). Secondly, students rarely have the opportunity to articulate their mathematical thinking, either verbally during class discussions or in writing as explanations of solution steps (Boaler, 2016). Thirdly, learning tends to be isolated from real-world contexts, rendering it challenging for students to comprehend the relevance of mathematical concepts to everyday experiences (NCTM, 2020). These factors collectively impede the development of students' mathematical communication skills.

To address this challenge, innovative learning approaches are required that can transform classroom interaction dynamics, facilitate students' mathematical expression, and establish connections between learning and practical scenarios. One learning model that is believed to fulfill these objectives is Project-Based Learning (PBL). PBL is an instructional strategy that positions students at the focal point of the learning process by engaging them in pertinent, real-world projects (Isrok'atun & Rosmala, 2021). This model possesses several defining characteristics: it is student-centric, product-oriented, grounded in authentic problems, promotes team collaboration, and encourages in-depth investigation (Krajcik & Shin, 2014).

Theoretically, Problem-Based Learning (PBL) can enhance Mathematical Communication Skills (MCS) by fostering students' engagement in discussions, idea expression, report preparation, and presentation of their work. Research conducted by Asmi et al. (2022) indicates that implementing PBL in mathematics classes can positively impact the MCS of junior high school

students. Furthermore, Novalia et al. (2025) and Almulla (2020) demonstrate that PBL not only improves MCS but also enhances students' learning engagement and collaborative abilities. Farokhah et al (2021) also reports a notable enhancement in MCS following the implementation of PBL in mathematics learning.

Despite numerous studies demonstrating the efficacy of Project-Based Learning (PBL), Chen and Yang's (2019) literature review and meta-analysis identified several limitations that warrant further attention. Firstly, the majority of PBL studies conducted in Indonesia have been conducted in urban schools with well-equipped infrastructure, while research in rural schools such as SMP Negeri 3 Sungai Lala, which face challenges in terms of technological access and exhibit diverse student abilities, remains relatively scarce. Secondly, there is a lack of clear guidelines regarding modifications to PBL approaches for eighth-grade algebra materials that cater specifically to the characteristics of low-performing students (Markula & Aksela, 2022; Hussein, 2021). Thirdly, moderating variables such as learning motivation and teacher support have not been comprehensively explored within the context of PBL mathematics (Bell, 2010). Lastly, there has been no longitudinal research investigating the long-term sustainability of MCS improvements following the conclusion of PBL interventions (Alashwal & Barham, 2025).

This study, based on the provided analysis, centers on two crucial aspects: contextualization and adaptive implementation. The contextual setting is a school situated in a rural region with limited resources. The adaptive implementation involves modifications to the project-based learning (PBL) design to align with the unique characteristics of 8th-grade students at SMP Negeri 3 Sungai Lala. One notable modification is the incorporation of locally relevant projects. Specifically, the budget calculation for micro, small, and medium enterprises closely associated with the students' lives aims to enhance their direct perception of the practical relevance of mathematics in everyday life. By employing this strategy, it is anticipated that students will exhibit increased motivation, active participation, and improved communication skills in conveying their mathematical concepts.

Based on the provided background description, the objective of this study is to assess the impact of implementing modified project-based learning (PBL) on enhancing the mathematical communication abilities of eighth-grade students enrolled at SMP Negeri 3 Sungai Lala. The study aims to contribute empirically to the understanding of the effectiveness of PBL in educational settings with limited resources. Furthermore, it will serve as a valuable reference for educators in designing interactive and contextual mathematics learning strategies that effectively foster the development of students' mathematical communication skills.

METHOD

This research employs a quasi-experimental study design with a quantitative approach to assess the impact of implementing the Project-Based Learning (PBL) model on students' mathematical communication abilities. The research design employed a Posttest-Only Control Design, wherein two groups of students (experimental and control) were compared following the administration of distinct treatments. The experimental group engaged in PBL-based learning that encompassed six primary stages: (1) initiating leading questions, (2) formulating project plans, (3) scheduling, (4) monitoring and mentoring, (5) analyzing test results, and (6) evaluating personal experiences. Conversely, the control group received conventional learning methods, including lectures and structured exercises.

The study was conducted at Sungai Lala 3 State Junior High School, which included the entire eighth-grade student population, comprising two parallel classes (N=60). This saturated sampling method was selected due to the relatively small population and its homogeneous academic characteristics (Sugiyono, 2016). To minimize selection bias, researchers randomly assigned the experimental and control groups. However, in real school settings, researchers encounter limitations in achieving perfect randomization (Cohen et al., 2017). Class 8-A (n=31) was designated as the control group, while Class 8-B (n=29) served as the experimental group.

The research instrument, a mathematical communication skills test developed based on the

indicators of the National Council of Teachers of Mathematics (NCTM, 2000), assesses three primary aspects: (1) the ability to articulate mathematical concepts in written form, (2) the capacity to comprehend and interpret mathematical representations, and (3) the proficiency in constructing logical arguments. This instrument underwent expert validation, demonstrating a Content Validity Ratio (CVR) of ≥ 0.62 (Lawshe, 1975). Additionally, a reliability test employing Cronbach's alpha yielded a coefficient of 0.84, indicating high reliability (Tavakol & Dennick, 2011). Data collection was conducted following a four-week intervention, while external variables such as learning duration, classroom environment, and teacher characteristics were controlled for.

Quantitative data analysis was conducted using SPSS version 21, employing the following stages: (1) Normality Testing: Shapiro-Wilk and Levene's Tests were utilized to assess the normality of data distribution and homogeneity of variance, respectively. (2) Hypothesis Testing: An Independent Samples t-test was conducted at a significance level of $\alpha = 0.05$ to compare the mean difference between the experimental and control groups. This comparison was based on the research hypothesis, which posits a significant difference in mathematical communication skills between groups taught using Project-Based Learning (PBL) compared to conventional methods. The hypothesis assumes that PBL fosters positive influence through collaborative activities and the completion of real projects, which encourage the articulation of mathematical ideas (Krajcik & Shin, 2014)

RESULTS AND DISCUSSION

This study seeks to assess the efficacy of the Project-Based Learning (PBL) model in enhancing the mathematical communication skills of 8th-grade students enrolled at SMP Negeri 3 Sungai Lala. Mathematical communication skills are a pivotal competency in contemporary mathematics education, as they encompass not only conceptual comprehension but also the capacity to articulate mathematical concepts concisely and logically (NCTM, 2000). In this context, PBL was selected as an intervention due to its attributes that emphasize real-world project-based learning, collaborative endeavors, and the articulation of ideas (Krajcik & Shin, 2014).

The experimental class implementing project-based learning (PBL) achieved an average score of 66.4 (standard deviation [SD] = 23.44), while the control class employing conventional methods only attained an average score of 52.0 (SD = 22.99). This disparity was not limited to the average score but also manifested in the distribution of scores, where the experimental class exhibited a maximum score of 100 and a minimum of 10, whereas the control class had a maximum score of 84 and a minimum of 5. Statistical analysis employing an independent samples t-test corroborated that this difference was statistically significant ($t = 2.348$, $p = 0.022$). The effect size (Cohen's d) value of 0.62, as per Cohen's (1988) criteria, indicates a moderate effect, suggesting that PBL has a substantial impact on enhancing students' mathematical communication skills.

In the initial indicator, specifically the capacity to connect tangible objects, images, and diagrams with mathematical concepts, it was discovered that 85% of students in the experimental group successfully identified all the components of a cube in question number 1. In contrast, only 35% of students in the control group achieved this level of comprehension. This notable disparity can be attributed to the characteristics of PBL, which engage students in practical projects, such as constructing a cube model from actual materials, thereby facilitating their understanding of the correlation between physical objects and abstract mathematical concepts (Boaler, 2016). This outcome aligns with the findings of Krajcik and Shin (2014), who asserted that PBL is effective in fostering conceptual understanding through direct experiential learning.

The second indicator assesses students' proficiency in explaining mathematical concepts, particularly in constructing a cube and its diagonals. Notably, 78% of students in the experimental group successfully completed this task, whereas 78% of students in the control group drew a cuboid instead of a cube. Common errors observed in the control class included the inability to discern between a cube and a cuboid, as well as inaccuracies in drawing the diagonals. These findings corroborate Vygotsky's (1978) contention regarding the significance of social interaction

in the learning process. In the context of Project-Based Learning (PBL), group discussions facilitate mutual correction and enhance students' comprehension of geometric concepts.

In the third indicator, which assesses the ability to formulate conjectures, construct arguments, and formulate generalizations, 70% of students in the experimental class successfully derived the formulas for the surface area and volume of a cube through logical reasoning. In contrast, a majority of students in the control class (65%) provided answers without adequate explanations or simply wrote the final formula without the derivation process. These findings align with the research conducted by Asmi et al. (2022), which demonstrated that project-based learning (PBL) significantly enhances students' mathematical reasoning abilities through the investigative process of projects. Activities such as group discussions and presentations within PBL compel students to articulate their thoughts systematically, as advocated by Hattie (2017).

The fourth indicator assesses students' proficiency in applying mathematical concepts to solve practical problems, particularly calculating the surface area and volume of a cube-shaped pencil case. Notably, 80% of students in the experimental group successfully resolved this problem employing the appropriate procedure. In contrast, students from the control group frequently overlooked crucial steps or incurred calculation errors. This outcome aligns with Bell's (2010) contention that project-based learning (PBL) facilitates the application of mathematical knowledge to real-world scenarios through contextualized projects.

The successful implementation of project-based learning (PBL) in this study can be attributed to several key mechanisms that contribute to the enhancement of students' mathematical communication skills. Firstly, contextualizing learning materials through real-world projects, such as calculating the cost of constructing a cube from cardboard, has been demonstrated to enhance student engagement and motivation (Isrok'atun & Rosmala, 2021). These projects not only provide practical relevance to the curriculum but also facilitate the application of knowledge to real-world scenarios. Secondly, the PBL learning structure, comprising guiding questions, investigations, product creation, and presentations, offers a systematic framework that promotes the development of mathematical communication skills (Larmer et al., 2015). During these stages, students are encouraged to articulate mathematical concepts both verbally and in written form, while simultaneously honing critical thinking and collaborative abilities. Thirdly, the reflection process integrated into each stage of PBL serves as an internal feedback mechanism that enables students to assess, refine, and deepen their conceptual understanding, thereby enhancing the clarity in communicating mathematical ideas (Schwartz et al., 2009). Overall, the combination of authentic learning environments, structured activities, and continuous reflection positions PBL as an effective approach in supporting the attainment of 21st-century mathematical competencies.

Theoretically, this study contributes to the development of mathematics learning models by strengthening empirical evidence regarding the effectiveness of Problem-Based Learning (PBL) in the Indonesian educational context. The findings regarding the mechanisms by which PBL improves mathematical communication skills enhance understanding of how project-based learning can facilitate the development of complex mathematical competencies, encompassing not only procedural skills but also conceptual understanding and critical reasoning skills (Nathan & Sawyer, 2014). Consequently, the results of this study provide a more robust scientific foundation for integrating PBL into the mathematics curriculum at the secondary school level.

Practically, the findings of this study offer several recommendations that can be implemented in mathematics teaching practice. Firstly, mathematics teachers can consider PBL as an alternative learning strategy, particularly for materials that require deep conceptual understanding and higher-order thinking skills. Secondly, schools are advised to provide adequate training for teachers in designing and implementing PBL effectively, including classroom management and facilitating group discussions. Thirdly, the development of comprehensive assessment instruments is necessary to evaluate various aspects of mathematical communication skills, ensuring that assessments focus not only on final results but also on students' thinking processes during the learning process.

Despite its strengths, this study presents several limitations that warrant acknowledgment. Firstly, the relatively short duration of the study, spanning four weeks, restricts the ability to assess the long-term impact of Problem-Based Learning (PBL) implementation on students' mathematical communication skills. Secondly, the study sample was confined to a single school with specific characteristics, necessitating caution in generalizing the results to a broader population. Thirdly, the study failed to control for other variables such as students' initial motivation and teaching style, which could potentially influence learning outcomes.

In light of these limitations, several research directions emerge. Longitudinal studies are recommended to gauge the sustainability of PBL's effects over a more extended period. Furthermore, expanding the study's scope to encompass schools with diverse characteristics would enhance the external validity of the findings. Additionally, further research is warranted to examine moderating factors, such as the role of teachers and school support, in the success of PBL implementation (Pintrich, 2003). Lastly, the development of a more comprehensive instrument to measure various dimensions of mathematical communication skills is anticipated to provide a more holistic perspective on the impact of PBL on student competency development.

This study presents robust empirical evidence demonstrating that Project-Based Learning is substantially more effective than conventional methods in enhancing the mathematical communication skills of eighth-grade junior high school students. These findings hold significant relevance for the advancement of mathematics learning theory and have practical implications for improving the quality of mathematics education in Indonesia. Despite its limitations, this study serves as a foundation for further research on the implementation of PBL in diverse mathematics learning contexts.

CONCLUSIONS

This study provides compelling empirical evidence supporting the effectiveness of Project-Based Learning (PBL) in enhancing mathematical communication skills among eighth-grade students at SMP Negeri 3 Sungai Lala. The statistical analysis yielded significant results, with a t-value of 2.348 exceeding the critical t-value of 2.002 ($p = 0.022 < 0.05$), leading to the rejection of the null hypothesis (H_0) and acceptance of the alternative hypothesis (H_1). These findings robustly demonstrate that students taught using the PBL model achieved significantly better outcomes in mathematical communication compared to those receiving conventional instruction (Cohen, 1988).

The superiority of PBL manifests across all mathematical indicators of mathematical communication: (1) connecting real-world objects to mathematical ideas, (2) explaining concepts verbally and in writing, (3) formulating mathematical arguments and generalizations, and (4) applying mathematical knowledge to daily life situations. Particularly noteworthy was the 27.7% higher mean score achieved by the experimental group (66.4) compared to the control group (52.0), with an effect size (Cohen's d) of 0.62 indicating moderate practical significance (Lakens, 2013). These results align with previous research by Krajcik and Shin (2014) and Larmer et al. (2015), confirming PBL's efficacy in fostering deeper conceptual understanding and improved knowledge articulation.

The success of PBL in this context can be attributed to several key factors identified during the study. First, the authentic project-based approach facilitates meaningful connections between abstract mathematical concepts and concrete applications, enhancing students' ability to express mathematical ideas clearly (Boaler, 2016). Second, the collaborative nature of PBL created numerous opportunities for mathematical discourse and peer feedback, crucial components for developing communication skills (Vygotsky, 1978). Third, the structured presentation requirements in PBL compel students to organize and articulate their mathematical thinking systematically (Hattie, 2017).

These findings carry important implications for mathematics education practice and policy. They suggest that PBL should be seriously considered as a pedagogical alternative to traditional methods, particularly for developing higher-order mathematical competencies. The results also

highlight the need for professional development programs to equip teachers with effective PBL implementation strategies and appropriate assessment techniques for evaluating mathematical communication skills (NCTM, 2020).

However, several limitations should be acknowledged when interpreting these results. The study was conducted in a single school setting with relatively small sample sizes (N=60), which may affect the generalizability of the findings. Additionally, the short-term nature of the intervention (4 weeks) precludes conclusions about the long-term sustainability of the observed effects. Future research should address these limitations through longitudinal designs with larger, more diverse samples, while also investigating potential moderating factors such as teacher characteristics and school support systems (Pintrich, 2003).

In conclusion, this study makes a significant contribution to the growing body of evidence supporting PBL's effectiveness in mathematics education. The robust findings demonstrate that PBL not only improves mathematical communication skills but does so more effectively than conventional teaching methods. These results have particular relevance for educational reform efforts in Indonesia and similar contexts, suggesting that wider adoption of PBL could enhance the quality of mathematics instruction and better prepare students for the complex communicative demands of 21st-century mathematical literacy (OECD, 2018).

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